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Airborne GPS/INS Integration Processing Module Development

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Abstract

In order to meet the users' demand, who needs faster and more accurate data in geographic information, it is necessary to obtain and process the data more effectively. Now more effective data obtainments about geographic information is possible through the development of integration technology, which is applied to the field of geographic information, as well as through the development of hardware and software engineering. With the fast and precise correction and update, the development of integrate technology can bring the reduction of the time and money. To obtain fast and precise geographic information using Aerial Photogrammetry method, it is necessary to develop Airborne GPS/INS integration system, which makes GCP to the minimum. For this reason, this study has tried to develop a system which could unite and process both GPS and INS data. For this matter, code-processing module for DGPS and OTF initialization module, which can decide integer ambiguity even in motion, have been developed. And also, continuous kinematic carrier-processing module has been developed to calculate the location at the moment of filming. In addition, this study suggests a possibility of using a module, which can unite GPS and INS, using Kalman filtering, and also shows the INS navigation theory.

Keywords : *GPS, INS, Integration, GCP, Kalman filter*

1. Introduction

Geographic information systems(GIS) can be used as an appropriate tool for intention-decision when there is a very quick update with the GIS database construction. Almost all obtainments methods for the space data are aerial photography or satellite images. Another is the sensor's modeling through measurement of the ground control point(GCP). For the measuring of the GCP, it is necessary to spend a lot of time and money, so that this measurement causes many problems for the reducing the updating period of the data. In addition, when making raster map for the process various data, there are also problems, such as the validity for the selection of the GCP, or data process problem when there is no GCP.

In this study, global positioning system(GPS) in the airplanes and image-process technology are combined. And also this study does a research for the development of GPS/INS(inertial navigation system) integration data process system, which can develop an effective geometry correction technology for the various image data from airborne sensors. For this matter, code-processing module for differential GPS(DGPS) and on-the-fly(OTF) initialization module, which can decide integer ambiguity even in motion, have been developed. And also, continuous kinematic carrier-processing module has been developed to calculate the location at the moment of filming. In addition, this study shows the INS navigation theory and develops a module, which can unify GPS and INS, using Kalman filtering.

For this reason, in this study, GPS and various sensors are made to be synchronized and a synchronization module is built between GPS time and scanning time to calculate the external orientation parameters of the airplanes and satellites. And also time interpolation module is developed at the moment of filming. Each module developed is combined to the GPS/INS integration data processing system for measuring the aerial photography, and this study also shows the possibility of using those modules in reality through experiments.

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2. The Development of Integrated Module of GPS Data Process

2.1 The Development of Code-Processing Module for DGPS

DGPS is a very precise method of GPS measurement, and its measurement method is as following: First, a fixed receiver is attached on a point whose coordinates are known, which creates a correction measurement. One more receiver is set up on an unknown, movable point and its results can be compared and corrected with the measurement from a fixed point. The first precondition for the DGPS data process is that the error of the code pseudo-range between the fixed point and the movable one. Under the precondition mentioned, the same satellite from both the fixed point and the movable one should be searched, and in order to adjust this, elevation mask should be adjusted.

DGPS code-processing module consists of three steps as in Figure 1. The first step is the coordinates input for the fixed point. In the second step, the measurement and navigation data of the movable point and fixed one are calculated and stored, and the third step is for the results of the data process.

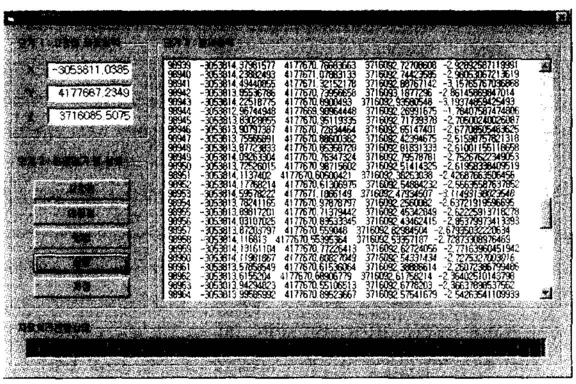


Fig. 1. DGPS code-processing module.

2.2 Search for the Integer Ambiguity of Carrier Phase and the Development of Program of Carrier Management

When more than four GPS satellites are observed at two observation points, the standard satellite will be the one which has the highest latitude. By making double differential equation for the measurement of carrier on the basis of the standard satellite, three-dimensional coordinates by centimeter for the movable observation point can be decided very precisely. Though carrier measurement is very precise, it has a disadvantage that integer ambiguity should be solved. In other word, the core of the precise location-decision by GPS is to solve integer ambiguity of carrier phase which is double differential.

In this study, using least-squares ambiguity decorrelation adjust(LAMBDA), the integer ambiguity will be tried to be solved.

The double differential equation using L1 and L2 carrier can be written as following.

$$\Phi^{kl}_{ij,1} = \rho^{*kl}_{ij} - \frac{I^{kl}_{ij}}{f_1^2} + \lambda_1 N^{kl}_{ij,1} + T^{kl}_{ij,1} + \varepsilon^{kl}_{ij,1}$$
$$\Phi^{kl}_{ij,2} = \rho^{*kl}_{ij} - \frac{I^{kl}_{ij}}{f_2^2} + \lambda_2 N^{kl}_{ij,2} + T^{kl}_{ij,2} + \varepsilon^{kl}_{ij,2} \quad (1)$$

To make the equation mentioned above linear, it can be made as following.

$$E\{y\} = Aa + Bb + e \quad (2)$$

In this equation, a and b are unknown variables, and A and B are the corresponding design matrix. Data vector, y is a known data, which is subtracted from the double differential data. Vector a is an integer ambiguity of double differential carrier, and it has an integer value. Vector b is a redundant unknown variable and includes ionospheric refraction, tropospheric refraction, and baseline vector. Generally, the equation above is executed through three steps.

In the first step, the integer ambiguity is adjusted by least squares when it is not limited to an integer. Under this condition, the integer ambiguity of the real number $\hat{a}$, unknown vector $\hat{b}$, and matrix($Q_{\hat{a}}$, $Q_{\hat{b}}$) for each are calculated.

In the second step, using the integer ambiguity of the real number and matrix, the searching range is reduced and the integer ambiguity of the integer is decided. At this moment, Z-transform is used to remove the dependency of double differential integer ambiguity.

$$z = Z^T a, \quad Q_{\hat{z}} = Z^T Q_{\hat{a}} Z \quad (3)$$

The third step is, using the equation below, to calculate the unknown variable, b, which is appropriate to integer ambiguity of the integer.

$$b = \hat{b} - Q_{\hat{b}\hat{a}}(\hat{a} - a)$$
$$Q_b = Q_{\hat{b}} - Q_{\hat{b}\hat{a}} Q_{\hat{a}}^{-1} Q_{\hat{a}\hat{b}} \quad (4)$$

The algorithm of the searching for the integer ambiguity of the integer is as following, and it searches for a, which meets the following condition.

$$\min(\hat{a}-a)^T\theta_{\hat{a}}^{-1}(\hat{a}-a), \quad a\in Z^m \tag{5}$$

The searching range should be limited to the inside of the circle, which meets the following condition, and then the integer value, which is the closest integer ambiguity of the real number, is calculated.

$$(\hat{a}-a)^T\theta_{\hat{a}}^{-1}(\hat{a}-a)\leq\chi^2 \tag{6}$$

In this routine, the integer ambiguity is already transformed with no dependency, and the necessary numbers of integer ambiguity is calculated. L1 GPSBP, which uses LAMBDA, is largely divided into the following three parts and programmed: data input and output through dialog boxes(CGPSDlg class), integer ambiguity solving by LAMBDA, and the calculation of the length of baseline and coordinates(CGPS class). Using Visual C++ 6.0, which is an object-oriented language.

The main window of baseline analysis program is made on the basis of dialog as in Figure 2. Figure 3 is for selecting the observation data files, and Figure 4 is the setup for the baseline analysis. In Figure 4, the satellite to remove from the data process is selected and the altitude angle is set. When there is a satellite with low altitude included, it can be removed while analyzing baseline. Figure 5 shows the results in editing box after baseline analysis, such as early altitude angle of observed satellite, double differential real number, double differential integer number, the coordinates of the fixed points, and the coordinates of the movable point.

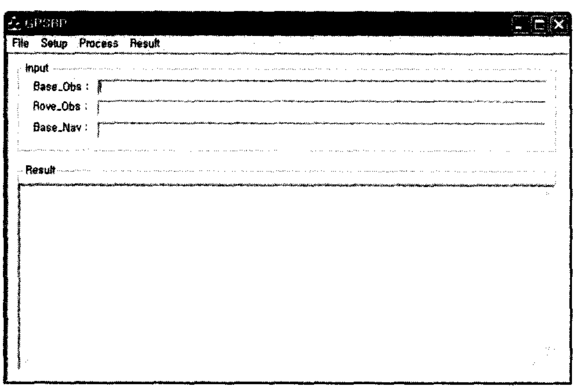


Fig. 2. The main window of data process.

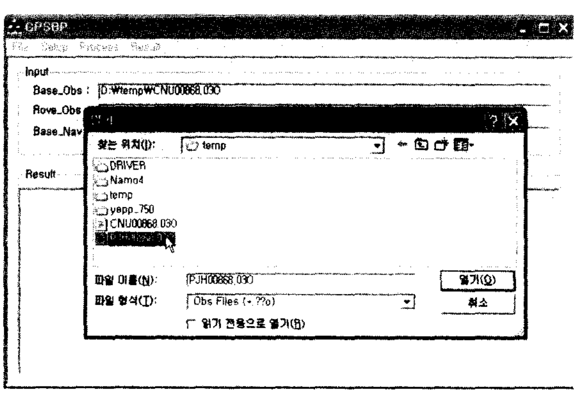


Fig. 3. The selection of observation and navigation files.

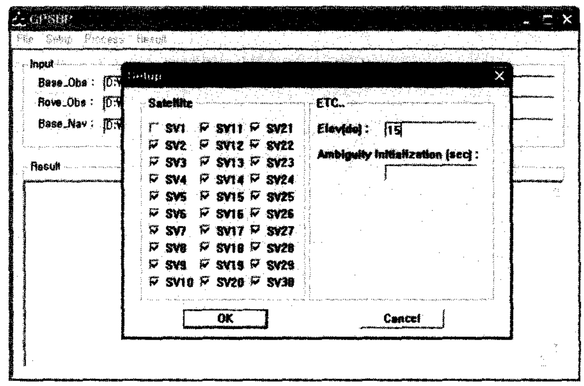


Fig. 4. Setup.

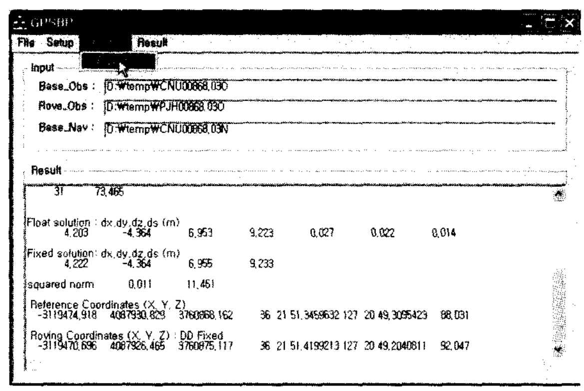


Fig. 5. The results of baseline analysis.

CGP class is largely composed of the following steps; inspection of the cycle slip, calculation of double differential real number, and decision of the integer ambiguity using Clambda class.

2.3 The Decision of the Integer Ambiguity Using LAMBDA

Using DAT2RIN.EXE, The data, which was observed through L1 receiver(Trimble 4000SE) for an hour from 23 o'clock, March 26, 2003, was transformed to RINEX form. After inspecting the cycle slip, using the program (GPSBP), the double differential real number was calculated.

For an hour, six satellites were consecutively observ-

Table 1. Calculated integer ambiguity.

Observed Satellite-Standard Satellite	double differential Real Number integer ambiguity (a)	Fraction part integer ambiguity (c)	Transformed integer ambiguity (d)	Transformed integer ambiguity (e)	integer ambiguity (f)
18 - 9	20.915	0.915	2.067	2	21
18 - 14	-10233.634	-0.634	0.94	1	-10234
18 - 15	-16.776	-0.776	1.082	1	-17
18 - 23	254395.94	0.94	-1.036	-1	254396
18 - 30	1480.844	0.844	-1.95	-2	1481

ed. In early observation, the 18th satellite's altitude was the highest, 84, so that it was chosen as the standard satellite and was double differential. The integer ambiguity calculated is as in Table 1, (a). To locate real integer ambiguity at the center of the circle, integer parts and real number parts are divided as in (b) and (c), and then only real number parts are calculated. (d) is the results of integer ambiguity. By using Chistart function, the appropriate value is decided, which has more than two integer ambiguity. Then the integer ambiguity, which is the nearest to real number integer ambiguity, is searched by Search function. (e) is the value of the nearer integer ambiguity of the two integer ambiguity to real number integer ambiguity. The integer ambiguity, which is calculated using equation (f) is as following.

3. The Development of GPS/INS Integration Data-Processing Module

3.1 Designing of the Linear Dynamic System for the Integration GPS and INS

The dynamic process of the inertia system errors is caused by the following reasons.

- The error from the sensors of the inertia system.
- The error from the movement of the sensor system.
- The error from the initialization of the inertia system.

This dynamic processor performs a process based on the following linear dynamic equation(7). State differential equation of the homogeneous system can be expressed like below.

$$\dot{\underline{X}} = F\,\underline{X} \tag{7}$$

$\underline{X}$ is a state vector and F is dynamic matrix. In this equation, a certain state vector should be put and it should be considered what kind of parameter should be modeled, which statistically belongs to the process noise. Generally, for strap down system, 15 state vectors below should be selected.

$$\underline{X} = [\delta\phi]\ \delta\lambda\ \delta h\ \delta V_N\ \delta V_E\ \delta V_D\ \varepsilon_N\ \varepsilon_E\ \varepsilon_D\ \delta\omega_x\ \delta\omega_y\ \delta\omega_z\ \delta a_x\ \delta a_y\ \delta a_z] \tag{8}$$

Each component of the dynamic matrix is referred to the reference. Generally the exact analytical solution for the differential equation above does not exist, but the solution can be obtained by the following numerical integration.

$$\underline{X}_k = \Phi(\Delta t)\ \underline{X}_{k-1} \tag{9}$$

Matrix can be obtained by Taylor series expansion using the dynamic matrix and time interval.

$$\Phi = e^{F\Delta t} = I + F \cdot \Delta t + \frac{1}{2} \cdot F^2 \cdot \Delta t^2 \tag{10}$$

When implementing a filter, time and updating period play an important role. For practical reasons, integer multiple of one second is selected for time interval, if possible. With this method, the amount of float calculation can be hugely reduced.

The error of inertia system increases on the basis of integration. The error does not increase continuously, but by the characteristic of differential equation, the error propagates with a period(84.4 min). The amplitude depends on the gyro in use and the error characteristic of the acceleration sensor.

The error, which infinitely increases according to time, can be decreased by periodical updating, based on the external observation. In the past, Doppler measurement and barometer were used as auxiliary equipments. However, the accuracy of these auxiliary equipments is very low, so they can not be used for this study. Only GPS can be used for the better accuracy for updating of position and speed.

To relate to the errors of inertia measurement, the externally measured value(GPS-position and speed) is used in Kalman filter through observation equation.

Additionally measured value is used in estimating the unknown values of state vector. The estimation of system error and sensor error are performed by the well-known Kalman filter, considering the processor noise and the measurement error.

Various GPS measured values are used according to the required accuracy and the level of the completeness. The results by GPS/INS, such as code phase, filtering carrier phase, or carrier, mainly depend on the accuracy of updating data. The best way is to use carrier. The uncertain integer can be determined using at least more than 5 satellites which are appropriately arranged. With continuous observation, there should be no loss of data. In this method, no reception of satellites during short term or cycle slip can be very insecure factors. While designing Kalman filter, which is related to the inertia data, uncertain value should be additionally used in state vector. With the limits of this program, the additional calculation is necessary for managing the state vector because the geometry of satellites changes frequently.

3.2 Synchronization

3.2.1 Hardware Setup

The external synchronization device performs the synchronization of GPS, IMU and various sensors for synchronizing hardware. This device is constructed to record the sensing time of the sensors through the external trigger, and at the same time, to make GPS know the event mark. The user can select a time interval(0.5 ~ 24 sec) using software and then this device controls the sensors periodically. At the same time, it is constructed to get the GPS information about sensing time by sending event mark to GPS receiver.

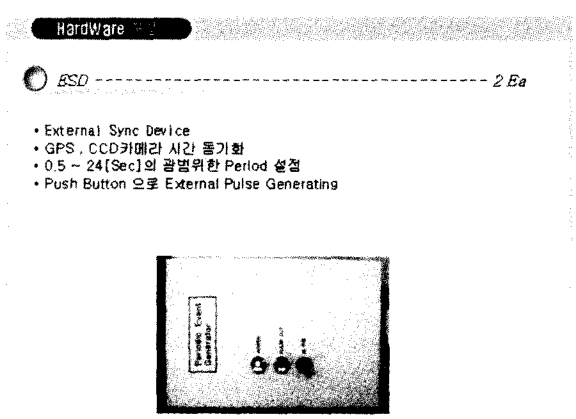


Fig. 6. Synchronization device.

3.2.2 Synchronization Process

This process is to synchronize the acquisition of GPS and inertial measurement unit(IMU), and it is a pre-process for the integration of GPS and IMU. For the synchronization, there are two steps, the process in hardware(H/W) and software(S/W).

- Hardware(H/W) Part

A signal is given to each data in GPS and IMU, using external synchronization device periodically, and then the basic data for synchronization is provided by marking points which are inputted at the same time.

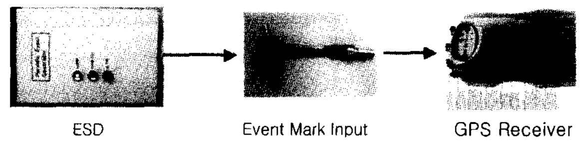
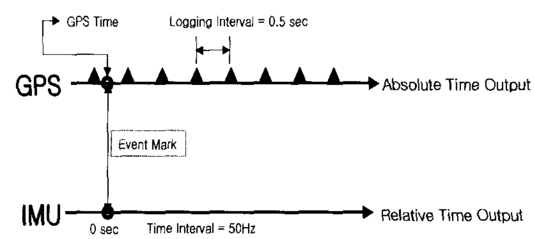


Fig. 7. Hardware setup.

- Software(S/W) Part

The timing between GPS and IMU is synchronized based on the marked information by external synchronization device(ESD). GPS time is standard and IMU data is linearly interpolated by 50Hz on the base of GPS time.



Time (sec) Sensor (C)	Roll (deg) Yaw Rate (deg/sec) Timer	Pitch (deg)	Roll Rate (deg/sec) X Accel (G)	Y Accel (G)	Pitch Rate (deg/sec) Z Accel (G)	Temp
0.000	0.868 0.019	−5.284 1.008	0.000 22.349	−0.124 0.018	−0.027	0.113
0.018	0.862 0.015	−5.295 0.997	−0.050 22.132	0.018 0.001	0.060	0.088
0.036	0.868 0.010	−5.279 1.000	0.087 22.349	−0.078 0.035	−0.027	0.081
0.053	0.873 0.023	−5.273 1.009	0.092 22.186	−0.220 0.017	0.064	0.094
0.072	0.879 0.024	−5.290 0.998	0.000 22.295	−0.124 0.051	0.156	0.103

Fig. 8. The raw data of IMU.

- The Transformation of Coordinates

This process is to synchronize the coordinates of each data for the integrate process of GPS and IMU. The coordinates transformation matrix is constructed as following.

$$C_b^n = \begin{vmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2 \end{vmatrix} \quad (11)$$

3.3 GPS/IMU Integration

INS has an advantage that it can continuously calculate the navigation information without any external help. It is not good to use inexpensive INS independently because the errors are accumulated as time goes on. In order to compensate this disadvantage of INS, there have been many researches to maximize the advantages of two systems by using GPS, which is a non-inertial sensor.

In this study, Kalman filter is used to integrate GPS and INS, and the following steps are performed.

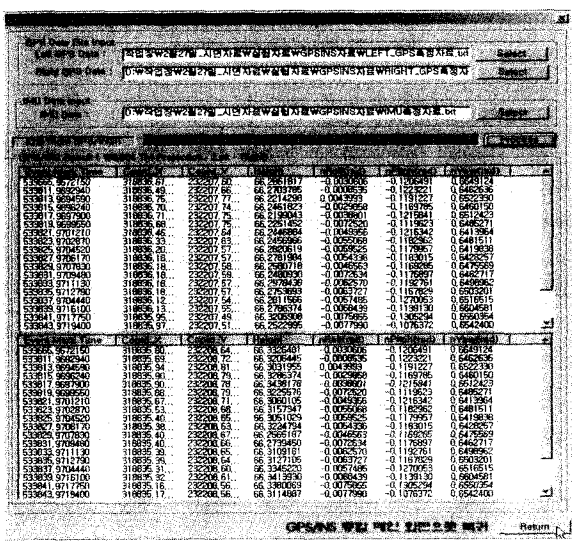


Fig. 9. GPS/IMU integration process.

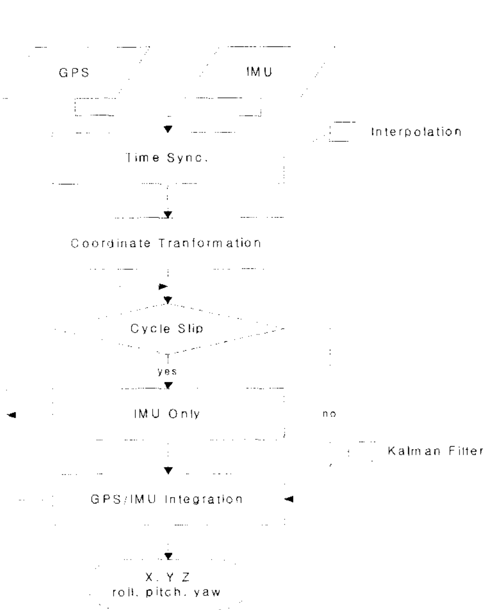


Fig. 10. GPS/IMU integration module.

4. GPS/INS Integration

The GPS/INS integration module is designed to decide the position and posture of the moving object. This module can decide the exterior orientation parameters of charge coupled device(CCD) image as well as enable the geo-referencing function of laser data.

In this study, simple union method is applied using Kalman filter for the integration GPS/IMU, and error correction model for Kalman filter is made for the better accuracy. In addition, ESD is used for the synchronization of GPS and IMU. The basic data for synchronization is provided by marking points which are inputted at the same time, and IMU data is linearly interpolated by 50Hz on the base of GPS time.

The calculation process using IMU data, is constructed to use measured values that are through sensor's regular error compensation, so that it can calculate the speed and position. For the calculation of posture, quaternion is used.

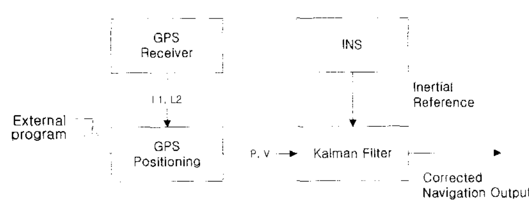


Fig. 11. GPS/INS Integration of simple union method.

4.1 Graphic User Interface(GUI) Design

GPS/IMU integrate has a GPS/IMU integration manager, which focuses on user's visuality and convenience. It can process without choosing any option. After loading of both GPS and IMU data, GPS/INS integration process is performed through GPS/INS integration manager.

As in the results of user's self-calibration, the results is shown in the tables to enhance user's readability. The confirmed results are automatically recorded in the memory for the next step.

4.2 Software Implementation

Figure 12 shows a module which is implemented, using object-oriented method, based on algorithm for the GPS/INS integration, mathematical model, and GUI design.

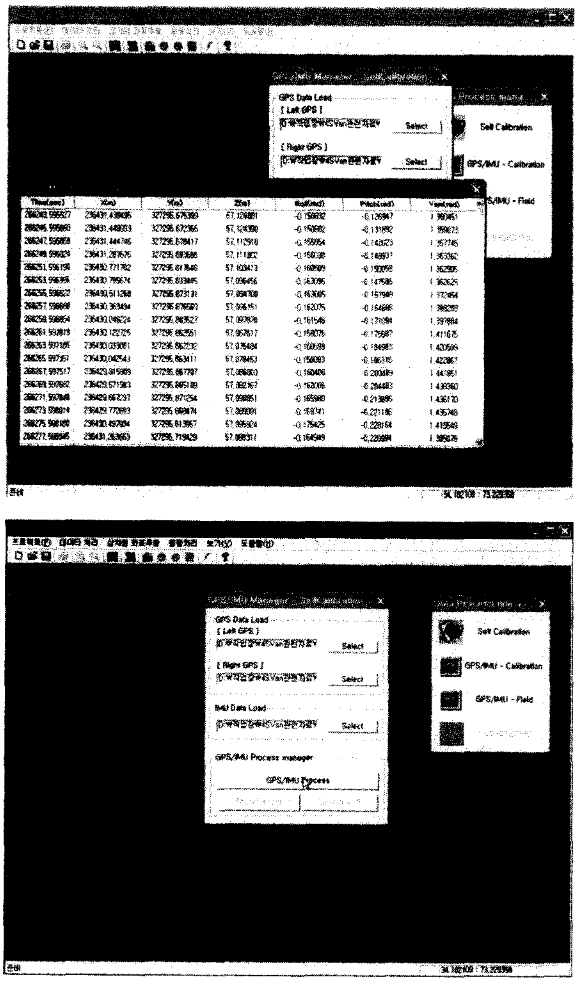


Fig. 12. The preparation for GPS/INS integration and the result.

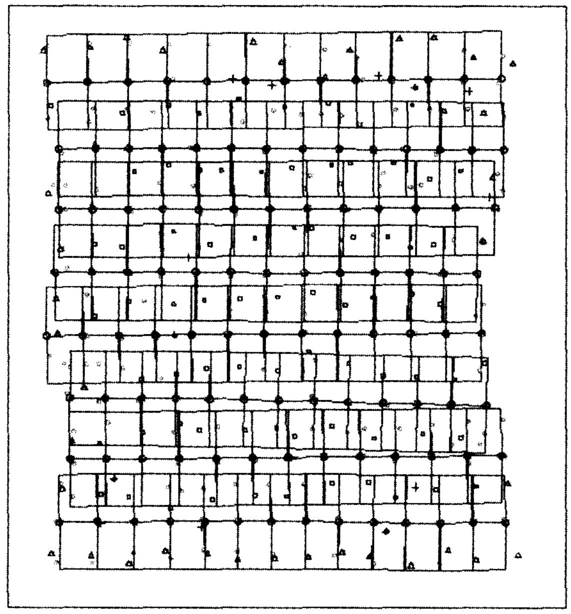


Fig. 13. The distribution of the all control points in the block.

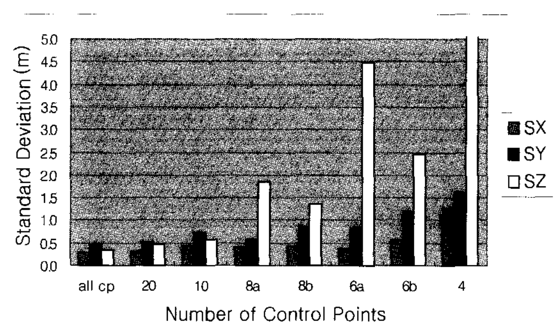


Fig. 14. The accuracy according to the number and arrangement of control points.

5. The Experiment of GPS/INS Integration System

In order to measure the photo control point, a photograph taken in Suwon area has been observed in detail to find the GCP in the picture and photo coordinates of the check point, using analytical plotter, P33. In performing GPS/INS navigation measurement, 1:20,000 has been used for photo scale, and the picture has been adjusted as the conventional navigation measurement method. Considered that the results do not have any error, they are compared with the accuracy according to the numbers of GCP.

The results has been analyzed by comparing to the results from GPS/INS navigation measurement. The software for the AT process has used the GPS/INS data as additional measurement, and also used a bundle managing method, BINGO, which can adjust combined blocks. Figure 13 shows all the distribution and arrangement of the control points.

Figure 14 shows the results of conventional AT according to the number of control points in the experiment. In case there are four control points, vertical error increases infinitely. If the graph exceeds 5m in the figure, the result diverges.

In case of conventional AT, the accuracy is proportionally decreased as the number of control points decreases. While the plane position responds to the number of control points less sensitively, height error considerably depends on it. When the number of control points is less than 10, height error already has an error of 2m. In addition, in case of less number of control points, the error is getting bigger. In the minimum case of four control points, it can be known that the adjustment is impossible and the results diverge.

Table 2. The accuracy of check points according to the number of points.

CP number	standard deviation(m)		
	Sx	Sy	Sz
all cp	0.28	0.46	0.35
20	0.32	0.51	0.46
10	0.42	0.73	0.58
8a	0.41	0.58	1.84
8b	0.42	0.86	1.36
6a	0.39	0.85	4.48
6b	0.59	1.17	2.38
4	1.26	1.61	23.8

Table 3. The GNS/INS data process setup with BINGO.

Classification	Amount	unit	Accuracy		
			Sx	Sy	Sz
tie point	202	μm	10	10	
pass point	127	μm	10	10	
GCP(X,Y)	38	cm	20	20	
GCP(Z)	110	cm			20
GPS		cm	30	30	30
INS		deg.	0.009	0.009	0.009

6. Conclusions

From GPS/INS integration process system development, which enables the acquisition of fast and accurate geographic information through aerial photogrammetry, the following conclusions can be obtained.

DGPS code-processing module has been developed through correction algorithm of systematic errors, which is included in GPS signals. The integrated GPS data-processing module has been developed by constructing integer ambiguity searching algorithm and carrier process algorithm.

For the synchronization of cameras and GPS/INS, hardware parts and software parts, which uses linear interpolation method, have been implemented. In order to combine GPS and INS, a design algorithm of linear dynamic system has been developed. GPS and INS have been combined by using Kalman filter. Based on the developed algorithm, the integration GPS/INS data-processing module has been developed.

In order to verify the integration GPS/INS system, the accuracy according to the control points has been analyzed. As results, it can be known that the proposed method can obtain higher accuracy with much less number of control points than the conventional method.

Based on the results of this study, the validity and usefulness of aerial photogrammetry system in GPS/INS have been obtained. Furthermore, it is expected that time and the cost of three dimensional geographic information will be reduced.

Acknowledgement

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